

Cosmic ray antiprotons and the Single Source model

*A.D. Erlykin ^{1,2} and A.W. Wolfendale ²

(1) P N Lebedev Physical Institute, Moscow, Russia.

(2) Physics Department, Durham University,
Durham, DH1 3LE, UK

October 8, 2015

1

Abstract

In view of the fact that the AMS-02 instrument has recently been used to make preliminary observations of the ratio of the antiprotons (\bar{P}) to protons (P) in the primary cosmic radiation we have returned to our idea of signatures of a local recent supernova. We find that at the present level of accuracy there is no inconsistency between our predictions for the \bar{P}/P ratio to some hundreds of GeV using the preliminary observations.

Keywords: cosmic rays, antiprotons, protons

1 Introduction

One of the most striking puzzles in cosmology is the baryon asymmetry of the Universe, i.e. the absence of antimatter in the visible part of it. Many experiments have been carried out to search for antimatter in primary cosmic rays (CR). So far all of them have given negative results. All the observed antimatter particles: positrons and antiprotons have been found to have a secondary origin, i.e. they are produced in the interactions of primary CR with the particles of the Interstellar Medium (ISM).

A most exciting discovery was made recently by the PAMELA collaboration, who showed that the energy spectrum and positron to electron ratio have an unusual energy dependence and cannot be explained by the positrons being entirely secondary particles[1]. This experimental result has been confirmed later by the Fermi-LAT [2] and, with high precision, by the AMS-02 [3] experiments. Many models have been proposed to explain the observations and among them our model of the Single Source [4].

¹*Corresponding author: tel +74991358737
E-mail address: erlykin@sci.lebedev.ru

Initially the Single Source model was proposed for the explanation of the evident sharpness of the knee in the primary CR energy spectrum at an energy of about 3-4 PeV [5]. It was based on the obvious non-uniformity of the ISM and of the distribution of stars in space. It assumes that the knee is caused by the contribution of a nearby and recent supernova remnant (SNR). We think that the most likely candidate for such a SNR is Vela SNR [6].

The excess of positrons is observed at an energy by 4 orders of magnitude less than that of the knee, so that the source of the positron excess should be different from that responsible for the knee. We suppose that the most likely candidate for such a positron source in the sub-TeV energy region is the Geminga SNR. We made the case for the positrons being derived from radioactive nuclei generated in the SN explosion [4].

Recently the AMS-02 collaboration have presented the preliminary results of the search for another antimatter particle - the antiproton. They show that in about the same sub-TeV energy region: from 20 GeV to 450 GeV, the \bar{P}/P ratio stays constant [7]. This behaviour cannot be explained by the secondary production of antiprotons from ordinary CR collisions.

In what follows we examine the situation with CR antiprotons on the basis of the Single Source model, i.e. the possibility of explaining the unusual behaviour of the \hat{P}/P ratio by the contribution of the recent nearby SNR.

2 The antiproton - proton ratio

2.1 General remarks

As with the situation for positrons the flux measured at Earth comprises a background component, due to CR interactions in the ISM and a (possible) component due to a discrete source. The latter component is very clear in the positron case but less so for antiprotons, as yet. The background is a crucial part of the analysis and this will be considered first.

2.2 The antiproton background spectrum

Many factors contribute to causing significant uncertainty in the background (see [4, 8] for details). We ourselves have made an independent estimate, being careful to include the contribution from helium nuclei (He) in the CR and in the target interstellar medium (ISM).

Our analysis is based on the model calculations of antiproton production in PP, PA and AA - interactions made using EPOS-LHC and QGSJET-II-04 codes [9]. The advantage of this work is that it uses the most advanced Monte Carlo generators tuned to numerous accelerator data including those from the Large Hadron Collider. The sample of projectile and target nuclei covers all major CR nuclei: P, He, CNO, Mg-Si and Fe for projectiles and P, He for targets. The energy range covered by these calculations is from 1 to 10^4 GeV/nucleon, i.e. it is adequate for the analysis of the available experimental data. The results are given in numerical tables which are useful for the precise calculations.

The numerical results of this work are given for so called Z-factors. They are defined as spectrally averaged energy fractions transferred to antiprotons assuming that the spectra of CR species in the relevant energy range can be approximated by a power law: $I_i(E) = K E^{-\alpha}$. Values of the spectral index α vary from 2.0 to 3.0. The Z-factors are expressed via the inclusive cross-section for the production of antiprotons $d\sigma/dz$, $z = E_{\bar{P}}/P$, as $Z = \int_0^1 dz z^{\alpha-1} \frac{d\sigma}{dz}$. The contribution q^{ij} of the particular inclusive reaction $i + j \rightarrow \bar{P} + X$ to the antiproton flux can be calculated as $q^{ij} = n_j I_i Z^{ij}$. Here, n_j is the number column density of the target nuclei. We adopted an ISM consisting of protons (70%) and helium nuclei (25%); heavier nuclei contribute no more than a few percent of the total number.

In order to convert inclusive cross-sections to inclusive spectra of produced antiprotons, the Z-factors were multiplied by the column density of the interstellar gas passed by the projectile nucleus (P or He) during its life in the Galaxy. It is taken as $cT\rho$, where c is the speed of light, T is the life time of the projectile particle in the Galaxy and $\rho = 0.5 \text{ cm}^{-3}$ is the density of the ISM. The life time T depends on the rigidity R of the particle as $T = \tau_0 \cdot R^{-0.5}$, where for $R = 1 \text{ GV}$ $\tau_0 = 4 \cdot 10^7 \text{ year}$. After the antiprotons are produced they begin to diffuse and finally annihilate or escape from the Galaxy. We assumed that their life time in the Galaxy against the escape is the same as for protons. The annihilation cross-section for antiprotons is taken from approximations used in the CORSIKA6500 code.

The results of our calculations are shown in Figure 1. They are compared with the \bar{P}/P ratio measured in the PAMELA and AMS-02 experiments [1, 7]. Contributions from P+ISM and He+ISM reactions are given separately and their sum is plotted by the full line. It is seen that the contribution of He-induced reactions does not exceed $\sim 30\%$ of the total. No normalisation is applied in the comparison and the excess of the experimental \bar{P}/P ratio over the calculated background is clearly seen at energies above 20 GeV/nucleon.

The experimental uncertainties are shown by the vertical error bars. The uncertainty of the calculations is difficult to estimate because, as it has been shown above, there are many input parameters with their own uncertainties. Some of the uncertainties are reduced in the ratio of \bar{P} to P , in comparison with the actual separate particle intensities, but not all. It can be noted that the resulting discrepancy at 1 GeV, $\Delta \log(\bar{P}/P) \approx 0.33$ is similar to the root-mean-square of the uncertainty of each of the constituents, estimated by us as 0.32.

Before continuing, some remarks about the validity of the derived background are necessary. Inspection of the literature indicates a range of predictions, most notably that of the exponent of the energy spectrum beyond some tens of GeV. It is self-evident that it should be 'large' because the Galactic lifetime of CR varies as, approximately, $E^{-0.5}$ and the lifetime factor appears twice in the \bar{P} intensity but only once in the P intensity. The steep energy dependence of the boron to carbon ratio (i.e. secondary to primary) is a case in point. Ours is similar to that given elsewhere [10]

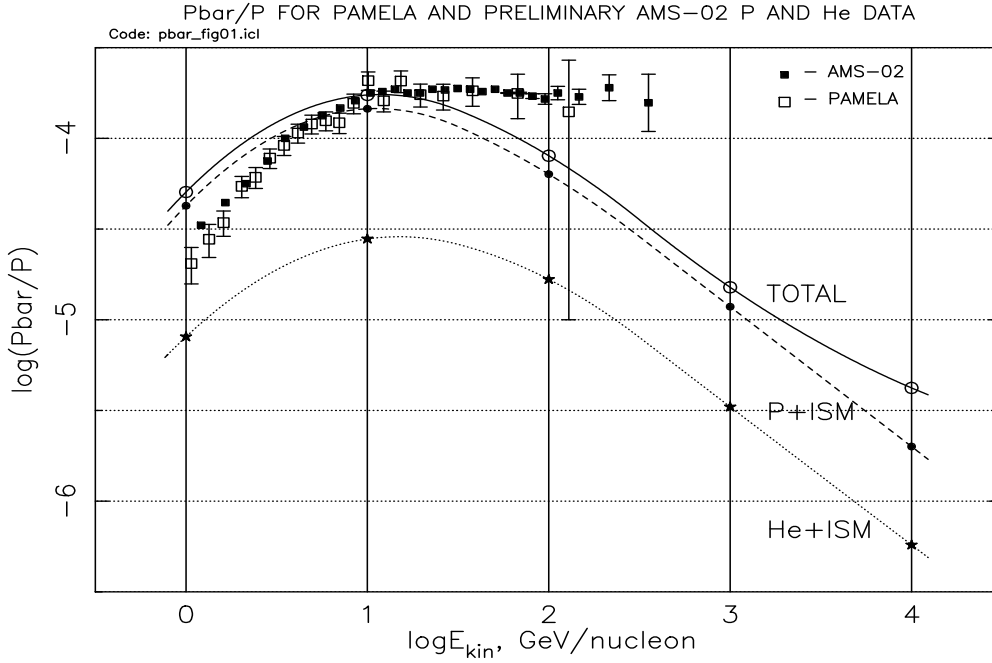


Figure 1: The antiproton to proton ratio measured by the PAMELA [1] (open squares) and AMS-02 [7] (full squares) experiments compared with the calculations. Contributions from proton and helium nuclei interactions with the ISM (P+He) as well as their sum are shown as dashed, dotted and full lines; denoted as P+ISM, He+ISM and TOTAL respectively.

2.3 Derivation of the energy spectrum of antiprotons produced by the Single Source

The AMS-02 collaboration presented actually the ratio of antiproton and proton intensities, in which the antiproton intensity is the sum of the background and the Single Source constituents: $\frac{I_{\bar{P}}^{bgd} + I_{\bar{P}}^{SS}}{I_P}$. Our calculations of the background have given the $\frac{I_{\bar{P}}^{bgd}}{I_P}$ ratio. Subtracting the latter from the former ratios we obtain $\frac{I_{\bar{P}}^{SS}}{I_P}$ ratio. Multiplying it by the experimental proton intensity I_P from [7] we obtain the energy spectrum of the antiprotons $I_{\bar{P}}^{SS}$ produced *by the Single Source*. The result is shown in Figure 2 in comparison with the energy spectrum of protons from the same Single Source taken from [11].

Insofar as the \bar{P}/P results are preliminary and there is a residual uncertainty in the estimate of the background the Single Source antiproton spectrum is imprecise. Nevertheless, the described calculations illustrate what should be eventually achieved. It is seen that protons and antiprotons have similar spectral shapes. It is due to the constant \bar{P}/P ratio and the dominant contribution of the Single Source to the total antiproton flux.

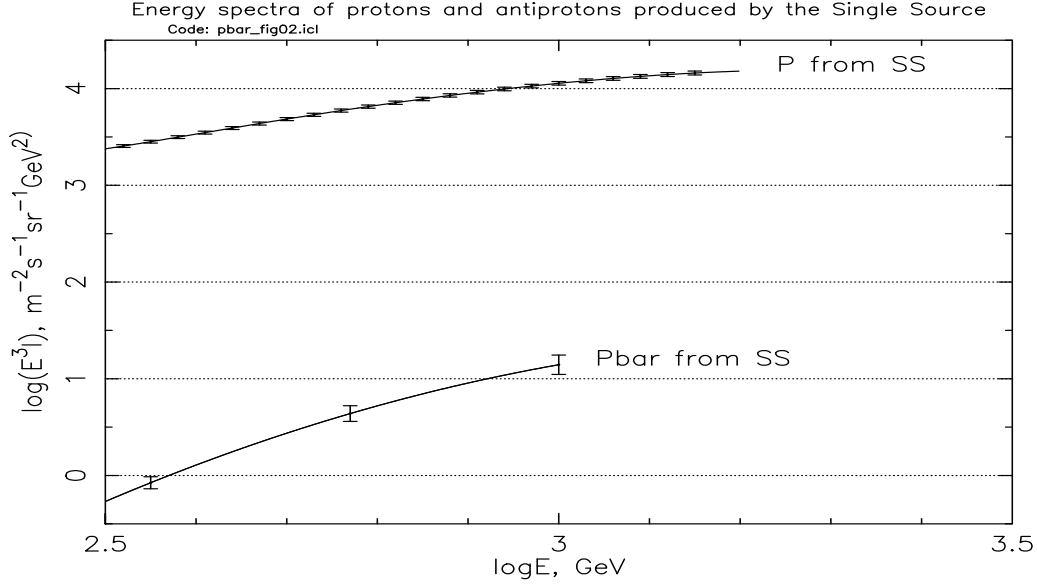


Figure 2: Energy spectra of protons and antiprotons from the Single Source.

2.4 On the way to the identification of the Single Source

Using our model of the acceleration and propagation of CR [12, 13] together with calculations of the antiproton production by various primary CR nuclei [9] we calculated the possible contribution to \bar{P}/P ratio of antiprotons generated by three nearby SNR: Vela, Monogem and Geminga. All are comparatively close to the Earth ($\sim 300pc$), but have substantially different ages. Vela is young ($\sim 10^4y$) and Geminga is much older ($\sim 3 \cdot 10^5y$). Due to its old age, the SNR associated with Geminga has disappeared, but a very powerful pulsar has been preserved. We selected these SNR, because our previous analysis indicated that Vela can be the source responsible for the knee at PeV energies [6] and Geminga is the candidate for the source of the positron excess [12] at sub-TeV energies. The result of our estimates is shown in Figure 3.

It is seen that the Vela SNR is so young that its accelerated protons and produced antiprotons of TeV energies have not reached the Earth and do not contribute to the \bar{P}/P ratio. On the opposite side, Geminga is so old that all the sub-TeV particles which can produce antiprotons have already gone. The shape and the absolute value of the Single Source contribution to the observed \bar{P}/P ratio is such that this source should be much more powerful than Geminga and younger to explain the unusual constancy of the ratio as a function of the energy. The Single Source should have characteristics 'intermediate' between these of Vela and Geminga.

One of the possible candidates is the Monogem Ring SNR with its pulsar B0656+14. It is at about the same distance of $\sim 300pc$ from the Earth as Vela and Geminga, but its age is intermediate between them. Derived from the period and spindown rate of the associated pulsar, its age is $\sim 10^5$ year. We have already discussed Monogem as a possible source responsible for the knee in the primary CR energy spectrum at 3-4 PeV [14]. This possibility arises, if during the SNR expansion, CR are confined inside

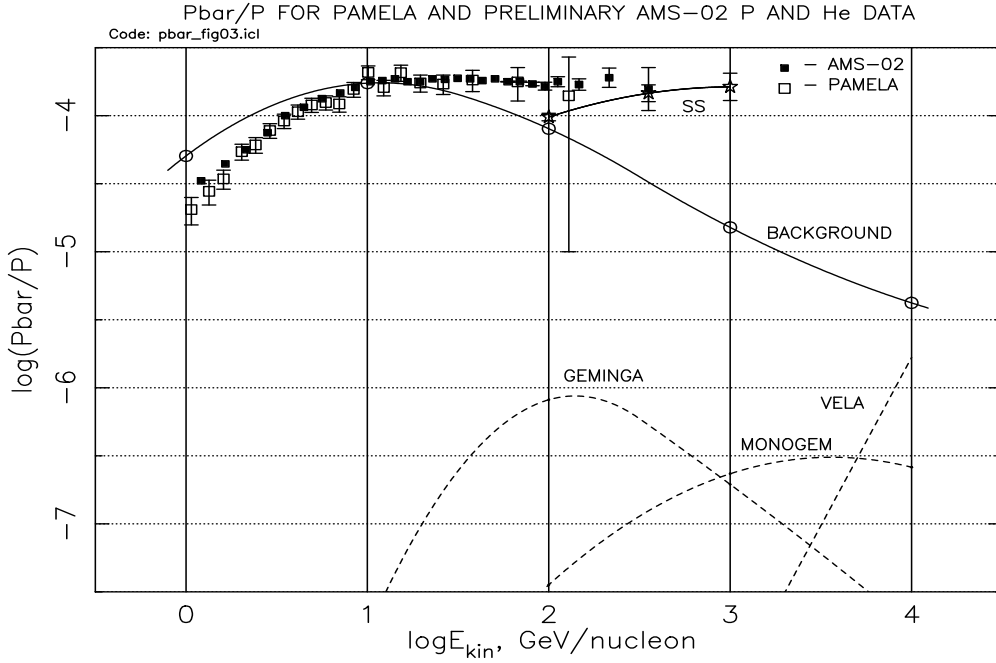


Figure 3: Antiproton to proton ratio measured in PAMELA and AMS-02 experiments compared with the possible contribution of three known sources: Vela, Monogem and Geminga SNRs. Contributions of the assumed Single Source and the background derived from the comparison of calculations and the experiment are denoted respectively.

the SN remnant for about $0.8 \cdot 10^5$ y and, in fact, emerged quite recently like CR from Vela. Recent more realistic models of SNR acceleration allow CR to escape from the remnant from the very beginning after the SN explosion, especially at high energies. Therefore, we consider now that CR emerge and propagate during its entire age of $\sim 10^5$ y for Monogem and $\sim 3 \cdot 10^5$ y for Geminga. In the process of propagation they collide with ISM atoms and produce antiprotons among other secondary particles. It is seen in Figure 3 that the Monogem gives flatter energy dependence of the \bar{P}/P ratio in the 0.1-1 TeV energy range compared with Geminga which is closer to the results of the AMS-02 experiment.

3 Conclusions

Our calculations show that the dominant contribution to the antiproton production is given by proton-induced reactions. Primary helium nuclei contribute no more than 30% of the total antiproton flux. The similarity of the produced antiproton and proton energy spectra derived for the Single Source can be explained if the Single Source is nearby and relatively recent to minimize the loss of high energy antiprotons due to the escape from the Galaxy.

Comparison with the measurements of the AMS-02 experiment shows that the Single Source model and the potential nearby sources such as Monogem and Geminga can be

responsible for the antiproton excess giving rise to the constant \bar{P}/P ratio if they are much more powerful than the standard SNR which converts 10^{50} erg of its energy into CR. An alternative, and possible contributory effect, arises if the SNR is accompanied by dense molecular gas - a not uncommon fact. The yield of antiprotons could then be considerably higher. A similar situation exists for the explanation of the results on the proton and helium spectra [11], where there was a shortage of one to two orders of magnitude in intensity; local gas has no relevance here, however. The Monogem SNR is better candidate than Geminga because it can give a flatter energy dependence of \bar{P}/P ratio at sub-TeV energies.

We conclude that with some reservations our Single Source model can give an adequate explanation of the preliminary \bar{P}/P results from the AMS-02 experiment.

Acknowledgements

The authors are grateful to the Kohn Foundation for financial support.

References

- [1] Adriani O et al 2009 *Nature* **458** 607
- [2] Ackermann M et al 2010 *Phys. Rev. D* **82** 092004
- [3] Aguilar-Benitez M et al 2013 *Phys. Rev. Lett.* **110** 141102
- [4] Erlykin A D and Wolfendale A W 2013 *Astropart. Phys.* **49** 23
- [5] Erlykin A D and Wolfendale A W 1997 *J. Phys. G: Nucl. Part. Phys.* **23** 979
- [6] Erlykin A D and Wolfendale A W 2015 *Bull. Russ. Acad. Sci., Phys.* **79/3** 308
- [7] AMS-02 coll., 2015 *Talks at the 'AMS days at CERN' 15-17.04.2015* **CERN**
- [8] Giesen G et al 2015 *arXiv:1504.0427*
- [9] Kachelriess M et al 2015 *arXiv:1502.04158*
- [10] Kohri K et al 2015 *arXiv:1505.01236*
- [11] Erlykin A D and Wolfendale A W 2015 *submitted to J. Phys. G: Nucl. Part. Phys.*
- [12] Erlykin A D and Wolfendale A W 2001 *J. Phys. G: Nucl. Part. Phys.* **27** 941
- [13] Erlykin A D et al 2003 *Astropart. Phys.* **19/3** 351
- [14] Erlykin A D and Wolfendale A W 2004 *Astropart. Phys.* **22/1** 47